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All-fiber 7x1 signal combiner for incoherent laser beam combining

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ABSTRACT

We demonstrate an all-fiber 7x1 signal combiner for incoherent laser beam combining. This is a potential key component for reaching several kW of stable laser output power. The combiner couples the output from 7 single-mode (SM) fiber lasers into a single multi-mode (MM) fiber. The input signal fibers have a core diameter of 17 μm and the output MM fiber has a core diameter of 100 μm . In a tapered section light gradually leaks out of the SM fibers and is captured by a surrounding fluorine-doped cladding. The combiner is tested up to 2.5 kW of combined output power and only a minor increase in device temperature is observed. At an intermediate power level of 600 W a beam parameter product (BPP) of 2.22 mm x mrad is measured, corresponding to an M^2 value of 6.5. These values are approaching the theoretical limit dictated by brightness conservation.

Keywords: Fiber lasers, beam combining.

1. INTRODUCTION

Development of rare-earth doped double-clad large-mode-area fibers and high brightness semiconductor pump sources have greatly increased the achievable output power of continuous wave single-mode fiber lasers. Today, the output power of these lasers extends well into the kW regime [1-5]. Stimulated Brillouin scattering, stimulated Raman scattering, thermal self focusing and facet damage limits the output power that can be obtained for a single-mode output [6]. Coherent or incoherent beam combination of fiber lasers enables further scaling of the output power. To obtain coherent beam combination single-frequency lasers with control of the phase of each source is required. This is necessary to ensure constructive interference in the combined beam. Incoherent combination on the other hand does not require phase control. This results in a simpler system but also in a less spectrally pure combined beam [7]. Free space setups for incoherent spectral beam combining have shown great potential and combined powers of up to 2 kW has been reached with near diffraction limited beams [8,9]. Recently, tapered fiber bundles of single-mode fibers have shown potential in making all-fiber components for incoherent beam combining [10]. The fabrication technique of these signal combiners is similar to what is used for making 1x7 fused couplers [11] and for making multi-mode to single-mode splitters [12,13]. With a tapered fiber bundle approach, bulk optical components are not necessary, thereby allowing for robust and stable components.

2. COMBINER FABRICATION

The combiners are fabricated using filament based GPX glass processing stations from Vytran [14]. These stations are used for fusing of bundles, tapering and splicing. Figure 1(a) shows an illustration of the combiner. The signal fibers are step-index single-clad fibers with a core diameter of 17 μm and an outer diameter of 125 μm . A bundle of 7 of these fibers is inserted into a fluorine-doped glass capillary tube. This fiber filled capillary tube is fused and tapered down into a solid glass element. The tapered element will act as a MM waveguide with a core that consists of the fused SM fibers and a cladding formed by the low-index capillary tube. Figure 1(b)-(d) shows images of the fused and tapered bundle cross-section along the length of the taper. The tapered MM fiber tip is spliced to a MM fiber with a core diameter of 100 μm , an outer diameter of 660 μm and an NA of 0.22. In order to increase the mechanical strength of the splice, the outer diameter of the MM fiber is reduced by a chemical wet etching process. Figure 1(e) shows a cross-sectional image

of the etched MM fiber. To avoid back-reflections into the signal combiner, the MM fiber is fitted with a high-power connector from Optoskand.

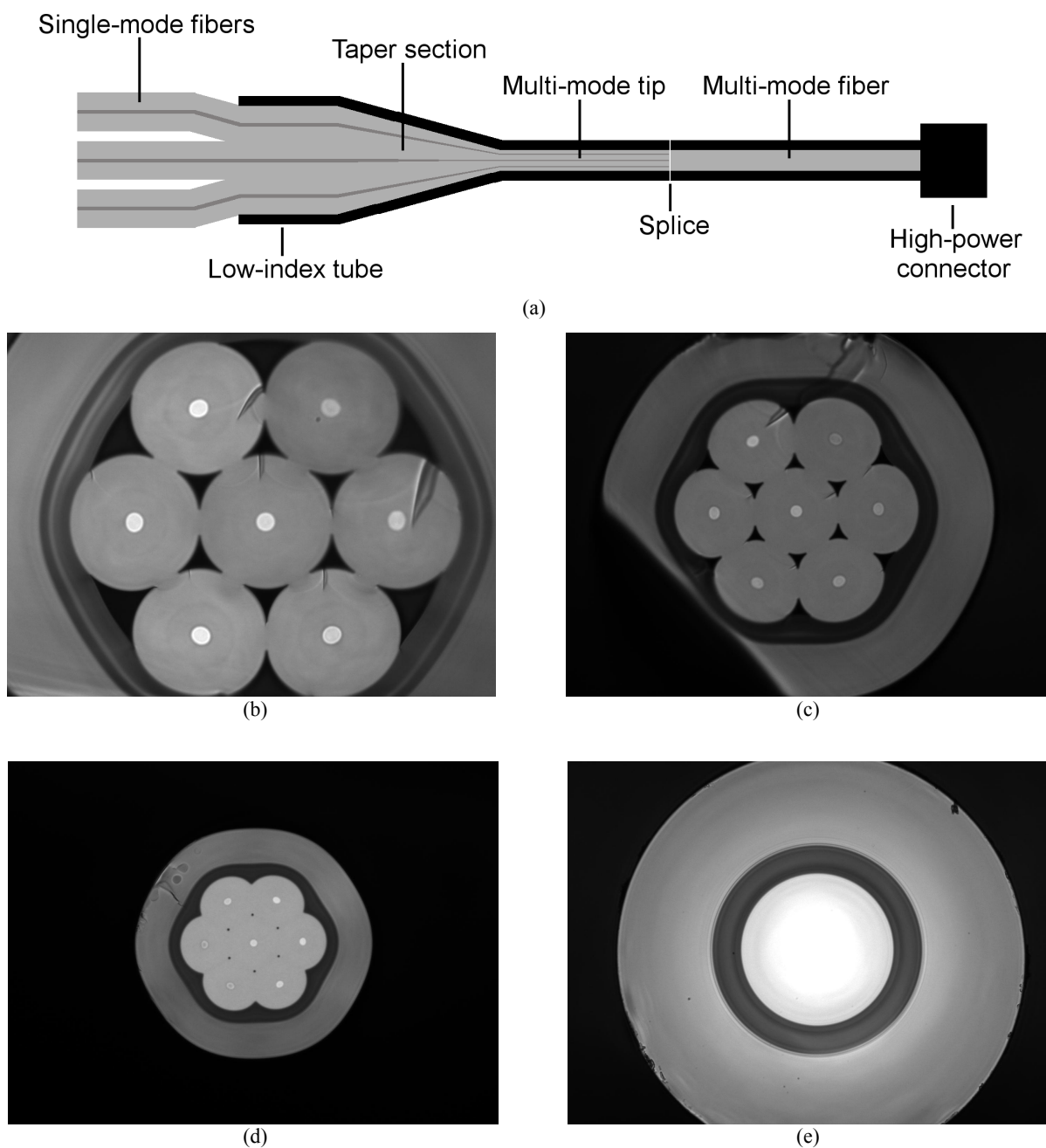


Figure 1. (a) Schematic illustration of the signal combiner. (b)-(d) Images of the taper cross-section along the length of the taper. The diameter of the 7 fibers is 255 μm , 159 μm , and 95 μm , respectively. (e) Image of the multi-mode fiber facet. In the image the fiber is etched to better match the outer diameter of the fused bundle. The diameter of the core is 100 μm .

3. HIGH POWER CONNECTOR

The standard Optoskand QBH connectors are internally water-cooled, include a mode-stripping section and an optically bonded fused silica end-cap. The exit surface of the end-cap is anti-reflection coated, which reduces the overall losses in the connector. The connector is designed for withstanding very high levels of back-reflection from the work piece as might be the case in material processing. It is specified to handle 5 kW of average power and has a loss of less than 3%. Instead of a full QBH connector, the fabricated signal combiner is fitted with an open fiber connector, see Figure 2. This connector consists of an aluminum holder where the MM fiber with the bonded anti-reflection coated end-cap is fixed. To keep the connector in position, a QB conical guiding sleeve is fixed to the holder. Since the holder is only air-cooled no mode-stripper was applied to the fiber in the vicinity of the end-cap. This is normally unproblematic since only low levels of back-reflection are expected in the testing of the device.



Figure 2. Open QB pig-tail connector.

A crucial point to achieve high performance with low losses is to make a strong optical bond between the fiber and the end-cap. Figure 3 shows the defect-free optical bond between a 100- μm -core fiber (outer diameter 660 μm) and a fused silica end-cap seen through the 20 mm long end-cap. Having an un-doped core of the fiber in combination with a pure silica end-cap implies no refractive index step in the optical bond, minimizing losses and back-reflections.

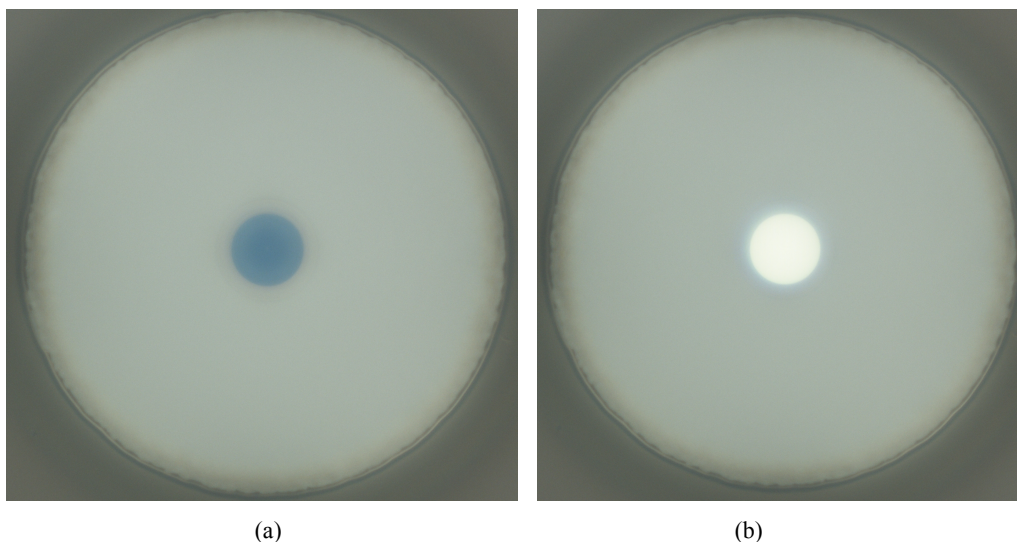


Figure 3. Optical bond between 100- μm -core fiber and fused silica end-cap seen through the end-cap. (a) shows a purely front illuminated image and in (b) white light is guided in the core.

4. OPTICAL TESTING

The combiner is first characterized at low power. The transmission loss of the combiner, the optical far-field and the M^2 value when 7 signals are combined is measured. All measurements are made with a fiber laser delivering an output power of ~ 1 W at a wavelength of 1060 nm. For measuring the transmission loss, the fiber laser is in turn spliced to each of the signal ports of the combiner. The loss for each of the ports is measured and shown in Table 1. All of the ports have approximately the same low loss with an average value of 4.6%.

Port number	Signal loss [%]
1	3.8
2	4.6
3	5.4
4	4.9
5	4.5
6	4.9
7	4.4
Average	4.6

Table 1. Measured signal loss in the combiner for each of the 7 input ports.

By launching light into all of the 7 input ports of the combiner the combined optical far-field out of the MM fiber can be measured. This measurement is also made at low power with a combined output power of ~ 1 W and at a wavelength of 1060 nm. The measured NA filling corresponds to 95% of the light having an NA lower than 0.06. Using a Spiricon laser beam profiler the beam quality is investigated and the value for M^2 was found to be 6.8.

5. HIGH POWER FIBER LASERS

Three kW CW fiber lasers manufactured by Rofin-Sinar Laser GmbH are used for high power testing of the combiner. The lasers have a passive output fiber with a core diameter of 20 μm and give a single mode output with a BPP of $<0.4 \text{ mm} \times \text{mrad}$. The wavelength of operation is 1070 nm or 1080 nm. The kW class fiber lasers are based on an all-fiber oscillator. The output power can be scaled by the number of used pump diode lasers, which can be added easily by help of pluggable pump fiber connectors. A maximum of twelve pump ports is possible, thus maximum output power levels of 1.2 kW can be realized. The optical to optical efficiency is about 80% depending on the pump wavelength. For laser units (pump diode lasers plus all in fiber oscillator) electrical to optical efficiencies of up to 38% are achieved. The kW class laser units can be used for direct material processing or as a basis for multi kW, multi mode, but still high brightness, all in fiber beam combination.

6. HIGH POWER BEAM COMBINING

The three kW fiber lasers are spliced onto three randomly chosen ports of the signal combiner. These ports have the numbers 4, 6 and 7, and turned out to be the center port and two of the side ports spaced by one fiber. Splicing between the fiber laser delivery fiber and the combiner input fiber is done with a Fujikura large diameter fiber splicer. The splice loss is $\sim 4\%$. The power out of the three fiber lasers is simultaneously increased, such that the power into each of the input ports is approximately the same. The combined output power as a function of total input power is shown as the solid line in Figure 4. In the figure, the transmission loss of the signal light is shown as the dashed line. A linear behavior of the combiner is observed with no roll off at high powers and with an average signal loss of 5.3%. The highest achieved output power is 2.54 kW. At this power level the combiner dissipates 129 W of the signal, but only a minor increase in device temperature to 38°C is observed. This means that most of the light is successfully stripped off optically rather than being absorbed.

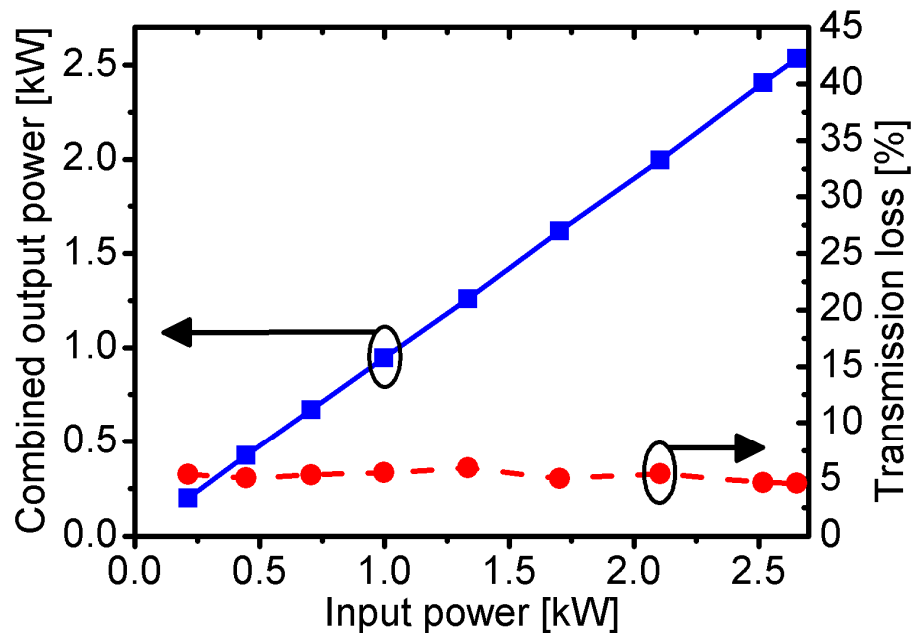


Figure 4. Combined output power as a function of total input power (solid line). Transmission loss of the signal light in the combiner (dashed line).

The beam quality is investigated with a Primes Focus monitor. This is done at a combined output power of 600 W. A beam parameter product of $2.22 \text{ mm} \times \text{mrad}$ is measured, corresponding to an M^2 value of 6.5. These measurements are in excellent agreement with the values measured at low power. The power distribution in the near-field of the MM fiber is shown in Figure 5. From the figure it is clear that the distribution is not uniform. A large peak in the intensity is seen

in the left side of the figure. By launching light into all of the ports of the combiner instead of only three, a more uniform distribution can be obtained. It is also believed that the distribution can be made more uniform by increasing the taper ratio of the fiber bundle. A larger taper ratio will result in smaller high-index inclusions in the tapered end of the fiber bundle. This means that the light will be less confined to these inclusions and instead more smeared out over the entire MM core.

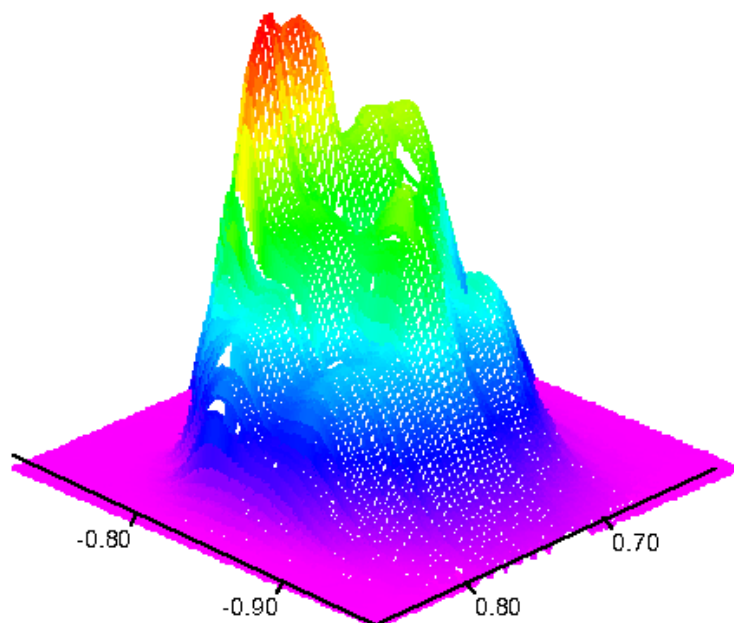


Figure 5. Power distribution in the near-field of the MM fiber at a combined output power of 600 W.

7. CONCLUSION

We have fabricated an all-fiber 7x1 signal combiner for incoherent laser beam combining. The 7 input fibers are step-index single-clad fibers with a core diameter of 17 μm . The output fiber is a MM fiber with a core diameter of 100 μm . A maximum combined CW output power of 2.5 kW is demonstrated with an M^2 value of 6.5. The signal loss in the combiner is $\sim 5\%$, which is effectively stripped away such that it does not damage any of the fiber coatings. The combined near-field showed peaks with very high intensity. By increasing the taper ratio of the fiber bundle, we believe that the near-field can be made more uniform.

8. ACKNOWLEDGEMENT

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